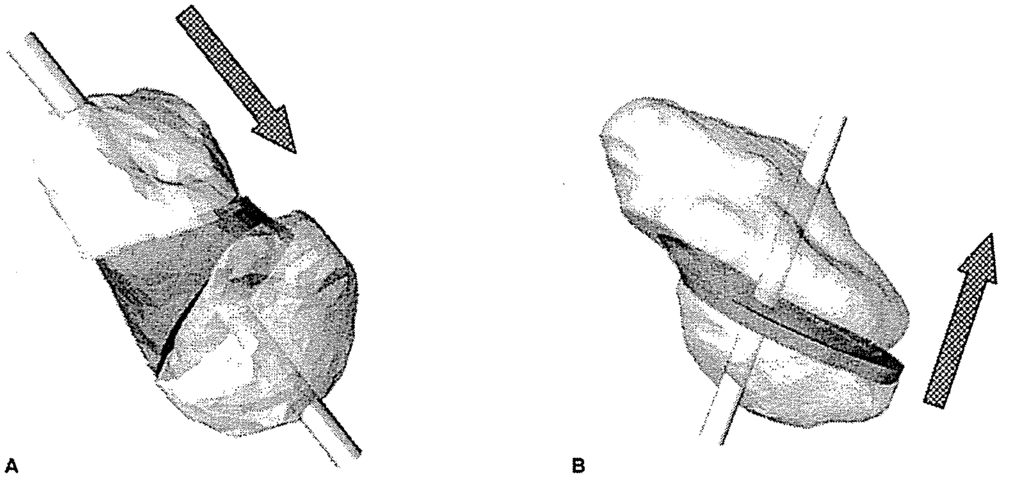

Figure 6. Pattern diagrams of bone grafting and screwing. (A) Distal type: wedge-shaped bone grafting and screwing from a volar approach is easier. (B) Proximal type: grafting of bone chips from the dorsal side is recommended. Screw insertion from the dorsal side allows it to penetrate the fracture site vertically.

bly maintaining stability of the distal fragment. In distal scaphoid fractures the fracture line is beyond the attachment of these ligaments so the fragment cannot resist flexion forces generated by axial loads, which result in a humpback scaphoid deformity.

Classifying patterns of bone defect into 2 types assists in selecting treatment strategies. Patients with proximal-type scaphoid nonunion who are of advanced age and do not have a physically demanding job may not need surgical treatment because alignment of the scaphoid should remain nearly normal for an extended period. Surgical treatment generally is required, however, when patients have symptoms indicating distal fracture, to prevent the fracture from proceeding to carpal collapse and degenerative arthritis. Moreover, choosing specific surgical approaches for each type may be preferable (Fig. 6). In distal fractures a wedge-shaped bone graft and correction of the humpback deformity are essential. A volar approach is recommended to allow easy correction of fracture deformity, implantation of the bone graft, and screw insertion (Fig. 6A). In proximal fractures scaphoid nonunion results in minimal bone defect or humpback deformity and massive osteophytes develop on the dorsal ridge. The fracture line in proximal fractures is thus more horizontal than in distal fractures. A dorsal approach is thus recommended and some degree of osteophyte resection around the fracture site and cancellous bone graft is adequate. Screw insertion from the dorsal side allows easier vertical penetration of the fracture site than a volar approach (Fig. 6B).

The amount of bone loss does not depend on the interval from injury. In distal fractures patients with injury duration of less than 12 months had bone resorption of more than 100 mm^3 whereas all patients with proximal fracture displayed bone defects of less than 100 mm^3 (Fig. 4). The amount of bone defect is affected by several factors such as patient activity, occupation, and duration of nonunion but it depends primarily on fracture location. Distal-type scaphoid nonunion tends to display symptoms earlier than proximal-type nonunion because of massive bone defect.

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In vivo three-dimensional wrist motion analysis using magnetic resonance imaging and volume-based registration

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Abstract

This study represents a new attempt to non-invasively analyze three-dimensional motions of the wrist in vivo. A volume-based registration method using magnetic resonance imaging (MRI) was developed to avoid radiation exposure. The primary aim was to evaluate the accuracy of volume-based registration and compare it with surface-based registration. The secondary aim was to evaluate contributions of the scaphoid and lunate to global wrist motion during flexion–extension motion (FEM), radio-ulnar deviation (RUD) and radial-extension/ulnoflexion, "dart-throwing" motion (DTM) in the right wrists of 12 healthy volunteers. Volume-based registration displayed a mean rotation error of 1.29° ± 1.03° and a mean translation error of 0.21 ± 0.25 mm and was significantly more accurate than surface-based registration in rotation. Different patterns of contribution of the scaphoid and lunate were identified for FEM, RUD, and DTM. The scaphoid contributes predominantly in the radiocarpal joint during FEM, in the midcarpal joint during RUD and almost equally between these joints during DTM. The lunate contributes almost equally in both joints during FEM and predominantly in the midcarpal joint during RUD and DTM.

Keywords: In vivo; Three-dimensional; Wrist kinematics; "Dart-throwing" motion; Volume-based registration

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Introduction

Motion analysis has seen wide application in studies of normal and pathological kinematics and the effects of reconstructive procedures on pathological conditions. Researchers have recently been able to non-invasively measure three-dimensional (3D) in vivo kinematics of the wrist joint using 3D images [3,10]. These systems enable the viewing and analysis of any in vivo motion of one bone relative to another one with any joint motion. Current techniques utilize image registration to determine corresponding relations between several image volumes represented at different coordinates via computerized tomography (CT) [1]. As radiation exposure is unavoidable during the course of CT-based motion analyses, we have utilized magnetic resonance imaging (MRI) for image acquisition to develop non-invasive techniques [12].

Recent approaches in kinematic studies predominantly concentrated on surface-based registration [1,3]. A drawback of such methods is that registration

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accuracy is limited to the accuracy of the segmentation step of the images. More recently, volume-based registration methods have been developed and may have an advantage in that feature calculation is straightforward to the point that the accuracy of these methods is likely to be insensitive to segmentation errors [2]. A combination of MRI and volume-based registration may therefore afford accurate, non-invasive, in vivo, 3D kinematic studies of the wrist.

Several studies have examined how global wrist motion is apportioned among the radiocarpal and midcarpal joints [8]. Most previous kinematic studies, however, only investigated wrist flexion–extension motion (FEM) and radio-ulnar deviation (RUD). Wrist radial-extension/ulnoflexion motion, known as "dart-throwing" motion (DTM), has also been considered as one of the most essential human wrist motions [4,15]. Kinematics of this motion, however, has only been investigated a few times [6,18].

The primary aim of this study was to evaluate the accuracy of volume-based registration and compare it with that of surface-based registration. The secondary aim was to evaluate the contributions of the scaphoid and lunate to global wrist motion during wrist FEM, RUD, and, specifically, DTM.

Materials and methods

Comparison of accuracy between surface and volume-based registration

MRI data from the wrist joint of a fresh normal cadaver was obtained using a 1.5-T commercial MR system (Siemens: Magnetom Vision PlusR 1.5T MRI) in conjunction with a receive-only surface coil (CP flex large). We employed a 3D sequence (3dflash) with TR/TE of 2.3 ms/33 ms and flip angle of 45°, a 160 mm field of view and 0.5 mm thickness on contiguous slices, with pixels of 0.6 × 0.8 mm.

Segmentation is defined as extracting bone regions and associating each region with individual bones. The anatomical structure or region of interest needs to be delineated and separated so that it can be viewed individually and reconstructed as a 3D bone model. Regions of individual bones were semi-automatically segmented from MR volume images using the Virtual Place-M® software developed in our laboratory (Medical Imaging Laboratory, Tokyo, Japan). This software generates 3D surface bone models by gathering pieces from all the slices, using the Marching Cubes technique [9]. From this software, we obtained surface models of each carpal bone, the ulna, and the radius without the cartilage using a Precision 650 DELL graphics workstation 3.20 GHz Pentium4 Xeno Dual Processor, 4 GB RAM.

Surfaced-based registration was performed using independent implementation of the interative closest point registration algorithm of Besl and McKay [1]. The method involves a two-step process. First, the closest point on one surface is computed for each point in a set of points representing the other surface. In this study, the first surface was a triangle set representation of the bone surface in the MR image, and the point set representation of the second surface was a set of surface points extracted from the other position image. Second, a transformation is determined by registering these two point sets. This process is iterated until some terminating criterion is satisfied. This method converges to a local minimum of the cost function, which is the root mean square (rms) distance between corresponding points at the final iteration.

Volume-based registration represents a method for determining relative positions between volume images represented at different coordinates, which means overlapping voxels in the intersection region of the baseline (target) and transformed images using a corresponding method based on correlation between voxel values. This overlapped region X_0 is set as the subset of voxel N_0 locations of the baseline image and $X_0 = \{X_0\colon X_0 \in X \cap T(X')\}$ where T is the rigid body transformation. The intensity of a voxel located at X_0 in the baseline image is denoted by $f(X_0)$, and the corresponding one in the transformed image by $g(X_0)$. The sets of intensities of the overlapping voxels of the baseline and transformed images are referred to as $F(X_0)$ and $G(X_0)$.

The normalized correlation coefficient (NCC) was used as a measure of similarity. Using this method, each carpal bone in one position was superimposed over images for each position. Relative motion of the carpal bones were then calculated by starting from initial translation parameters and finally finding the parameters allowing maximal correlation of the two images [2]. We sought the maximal NCC(F, G):

$$\mathrm{NCC}(F,G) = \frac{1}{N_0^2}\frac{\sum_{x_0 \in X_0}(f(x_0) - \bar{f})(g(x_0) - \bar{g})}{\sigma_f \sigma_g}$$

where $\bar{f}$ and $\bar{g}$ are the mean intensities of $F(X_0)$ and $G(X_0)$ and

$$\sigma_f = \frac{1}{N_0}\sqrt{\sum_{x_0 \in X_0}(f(X_0) - \bar{f})^2}, \quad \sigma_r = \frac{1}{N_0}\sqrt{\sum_{x_0 \in X_0}(g(X_0) - \bar{g})^2}$$

The experiment was conducted to determine and compare the accuracy from the two registration methods. Accuracies were evaluated using gold standards that were based on the parameters of the centroid position of fiducial markers. Fiducial markers were spheres of 7 mm diameter with oil inside that showed as hyperintense silhouettes on MRI. Markers were attached to the cadaver during image acquisition. The cadaver was scanned 10 times from different directions randomly using 3D-MRI. The position of a marker was defined by its centroid. An intensity-based centroid was calculated for each marker using the localization technique described in Wang et al. [16]. Validations of each registration were based on this transformation parameter of centroids. Ten registrations were examined in 10 MR images.

Motion analysis

Contributions of the scaphoid and lunate to global wrist motion were studied during wrist FEM, RUD, and DTM using MRI and volume-based registration techniques. The right wrists of 12 healthy volunteers (4 women and 8 men; age range 20–34 years, mean age 26.1 years) were studied. Each volunteer was positioned in the magnet in a lateral recumbent position with the elbow in 90° flexion during MR acquisition. Informed consent was obtained from each person according to institutional review board protocol.

For a global contribution study, images were obtained in three positions during wrist FEM, RUD, and DTM (a neutral position and the two extreme positions of each motion). Incremental contributions of the scaphoid and lunate were investigated during wrist FEM, RUD and DTM in five subjects. For the incremental contribution study, images were obtained in seven positions of FEM (60°, 40°, 20°, and 0° of flexion and 20°, 40°, and 60° of extension), RUD (radial deviation to 20°, 10°, and 0° and ulnar deviation to 10°, 20°, 30°, and 40°), and DTM (radial extension to extreme position and ulnar flexion to extreme position).

Accurate 3D visualization and estimates of relative positions and orientations of the capitate, scaphoid, and lunate relative to the radius were obtained using registration techniques and Euler angles. Euler angles represent the description of angular motions of a body in 3D space. Wrist motion was expressed as a ratio of radius/lunate or radius/scaphoid motion relative to radius/capitate motion. In-plane angles (sagittal plane corresponding to FEM, coronal plane to RUD, and oblique plane to DTM) of the radius/scaphoid, radius/lunate, and radius/capitate were measured directly from motion analysis data. The midcarpal joint (scaphoid/capitate, lunate/capitate) angle was calculated as the radius/capitate angle minus the radiocarpal (radius/scaphoid, radius/lunate) joint angle.

In studies of FEM and RUD, the coordinate system was constructed using ISB (based on the International Society of Biomechanics proposed standard definition for the wrist joint: http://www.

isbweb.org/standards/wrist.html). The origin is located between the radioscaphoid fossa and the radiolunate fossa. The Y-axis was defined as the line parallel to the long shaft of the radius with the long shaft axis corresponding to the minimum moment of inertia. The Z-axis was perpendicular to the Y-axis in a plane defined by the tip of the radial styloid, the base of the concavity of the sigmoid notch, and the specified origin. The X-axis was perpendicular to the Y and Z axes.

In the study of DTM, the dart-throwing plane was separately calculated for each subject and was defined as a plane that included the origin of the coordinate system and two centroids of the volume of the capitate at wrist extreme radial-extension and extreme ulnoflexion. Contributions of the scaphoid and lunate to global wrist motion during DTM were evaluated by calculating projection angles of each carpal bone to the dart-throwing plane. The calculated dart-throwing plane deviated 22.9° ± 8.8° ulnarly and pronated 17.2° ± 10.8° relative to the sagittal plane of the wrist in average.

Results

Comparison of accuracy between surface- and volume-based registration

Volume-based registration showed a mean rotation error of 1.29° ± 1.03° and a mean translation error of 0.21 ± 0.25 mm (Table 1). Surface-based registration had a mean rotation error of 1.67° ± 0.90° and a mean translation error of 0.19 ± 0.14 mm. Volume-based registration was more accurate in terms of rotation error ($p < 0.05$, two-tailed paired t-test). No significant difference in the translation components were noted between the two methods ($p = 0.503$).

Motion analysis

Different patterns of orientations relative to the radius of the capitate, scaphoid, and lunate were noted for FEM, RUD, and DTM (Figs. 1 and 2). The scaphoid contributed predominantly in the radiocarpal joint during FEM ($p < 0.001$), in the midcarpal joint during RUD ($p < 0.005$), and almost equally to both joints during DTM (Table 2). The lunate contributed almost equally in both joints during FEM and predominantly in the midcarpal joint during both RUD and DTM ($p < 0.05$, t-tests).

Table 1
Accuracy of surface- and volume-based registration for each carpal bone

	Carpal bone						
	Capitate	Hamate	Lunate	Scaphoid	Trapezium	Trapezoid	Triquetrum
Accuracy of surface-based registration							
Rotation error	1.70 (0.55)	1.26 (0.67)	1.91 (0.78)	1.36 (0.67)	1.38 (0.78)	2.20 (1.11)	1.87 (0.91)
Translation error	0.14 (0.09)	0.17 (0.17)	0.13 (0.14)	0.16 (0.08)	0.23 (0.13)	0.24 (0.19)	0.19 (0.11)
Accuracy of volume-based registration							
Rotation error	1.17 (1.01)	1.01 (0.76)	1.28 (0.72)	0.69 (0.35)	1.37 (1.55)	2.08 (1.64)	1.40 (0.79)
Translation error	0.12 (0.17)	0.23 (0.31)	0.14 (0.13)	0.17 (0.23)	0.32 (0.42)	0.37 (0.28)	0.24 (0.26)

An average of rotation and translation errors for each bone was measured. Rotation error unit: degree (standard deviation), translation error unit: millimeter (standard deviation).

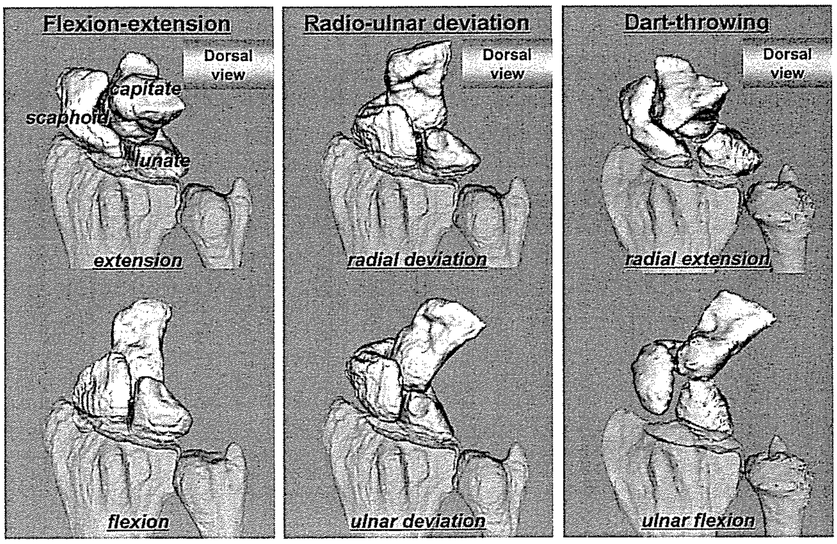

Fig. 1. Three-dimensional motion of the scaphoid, lunate, and capitate relative to the radius during flexion–extension (FEM), radio-ulnar deviation (RUD), and dart-throwing motion (DTM). In the dorsal view, each carpal bone moves in a different pattern. A part of the dorsal rim of the distal radius has been made translucent so that the proximal scaphoid and lunate can be seen clearly.

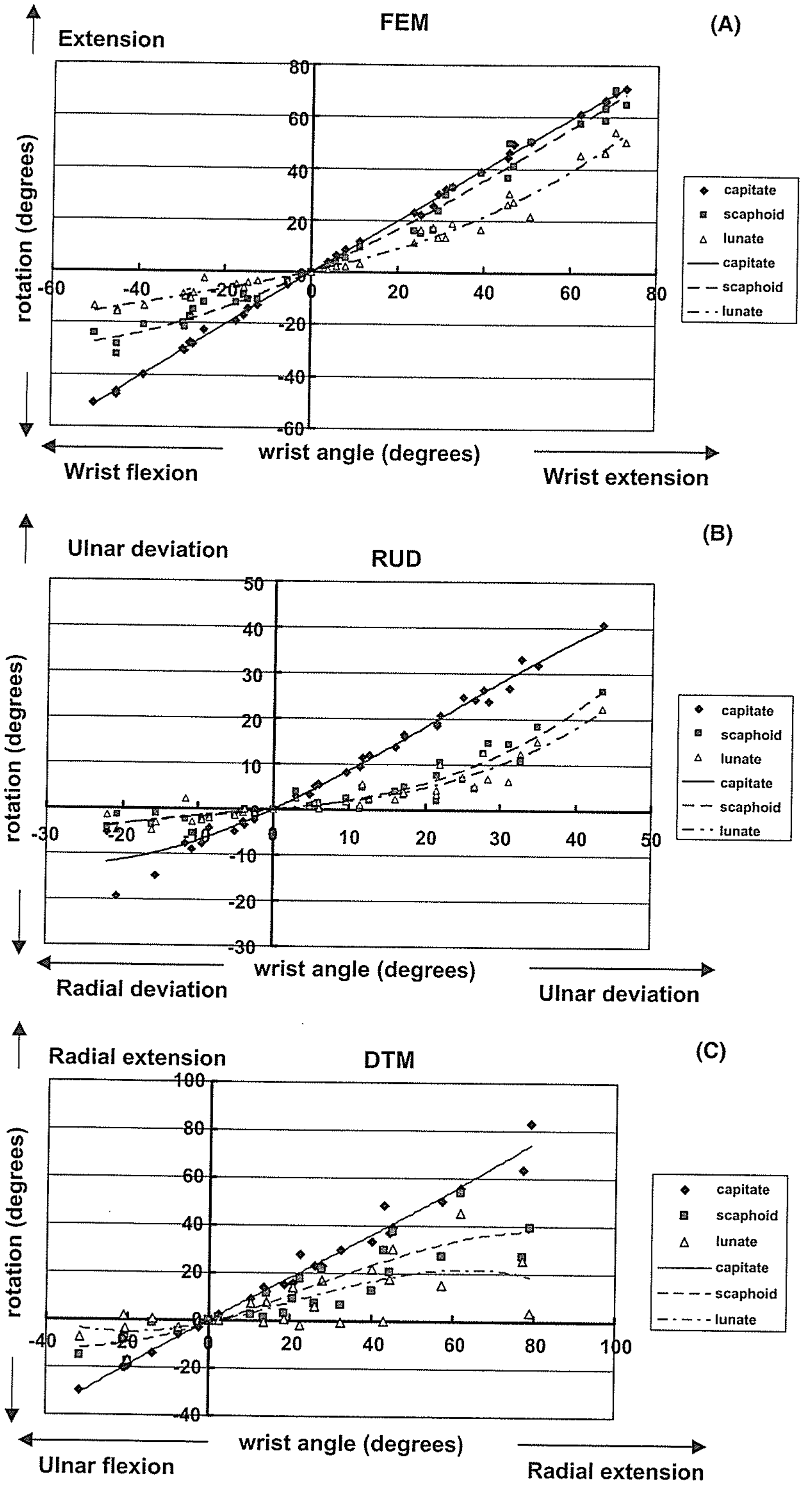

Fig. 2. Incremental contribution study of the capitate, scaphoid, and lunate: (A) flexion–extension motion, (B) radio-ulnar deviation, (C) dart-throwing motion. The vertical axis shows the rotation angle of carpal bones in-plane (in the case of FEM in-plane becomes the sagittal plane, but becomes the coronal plane during RUD and the oblique plane during DTM). The horizontal axis shows the angle of wrist position. The angle of wrist position is defined as the rotation angle of radiocapitate.

We found relatively great motion of the scaphoid despite of small motion of the lunate during DTM. In wrist radial-extension the scaphoid contributed 49.3% of capitate motion, and the lunate contributed only 21.7% in the radiocarpal joint. In wrist ulnoflexion, the scaphoid contributed 50.6%, and the lunate contributed only 31.1% in the radiocarpal joint. The ratio of scaphoid motion to lunate motion in the radiocarpal

Table 2
Global contribution of the scaphoid and lunate rotation to the radiocapitate rotation during flexion–extension (FEM), radio-ulnar deviation (RUD), and dart-throwing motion (DTM) for 12 subjects

Joint	Motion	Scaphoid				Lunate			
		Rotation (°)	SD (°)	Contribution (%)	AV (%)	Rotation (°)	SD (°)	Contribution (%)	AV (%)
FEM									
Radiocarpal	Ext.	52.0	8.5	88.9	81.7	38.8	10.8	63.4	56.4
	Flex.	23.5	6.1	69.7		13.9	5.7	43.2	
Midcarpal	Ext.	6.7	7.5	11.1	18.3	22.4	16.2	36.6	43.6
	Flex.	10.2	7.1	30.3		18.3	9.8	55.8	
RUD									
Radiocarpal	Radial dev.	3.4	2.0	24.8	36.0	3.3	2.7	28.0	36.8
	Ulnar dev.	12.8	5.8	40.9		12.6	5.6	40.1	
Midcarpal	Radial dev.	10.3	7.3	75.2	64.0	8.5	10.3	72.0	63.2
	Ulnar dev.	18.5	4.8	59.1		18.8	3.8	59.9	
DTM									
Radiocarpal	Radial ext.	27.1	12.1	49.3	49.6	12.0	7.5	21.7	26.4
	Ulnar flex.	7.8	5.9	50.6		3.3	6.1	31.1	
Midcarpal	Radial ext.	27.8	12.2	50.7	50.4	43.3	20.2	78.3	73.6
	Ulnar flex.	7.6	5.5	49.4		7.3	16.1	68.9	

Average rotation angle was measured from neutral wrist position to each extreme position. SD = standard deviation, AV = a contribution ratio of the scaphoid and lunate in the each carpal joint.

joint was 1.43 during FEM, 1.02 during RUD, and 2.28 during DTM. These results indicate scaphoid motion relative to lunate motion in the radiocarpal joint is greater during DTM than FEM and RUD.

During FEM, the scaphoid ($r^2 = 0.99$) moved in a ratio of 1:2 (midcarpal:radiocarpal joint) from full flexion to neutral wrist position, but from neutral to full extension, mainly moved in the radiocarpal joint. During RUD, the scaphoid ($r^2 = 0.91$) moved almost linearly and predominantly acted in the midcarpal joint from full radial deviation to 10° of ulnar deviation. But from 10° of ulnar deviation to full ulnar deviation, the ratio of midcarpal to radiocarpal joint gradually increased, and at the end the ratio became almost 2:3. During DTM, the scaphoid ($r^2 = 0.89$) moved almost linearly and with almost the same contribution ratio in the radiocarpal and midcarpal joints (Fig. 2).

During FEM, the lunate ($r^2 = 0.98$) moved in an almost linear manner in both the radiocarpal and midcarpal joints from full flexion to 30° of wrist extension, then the ratio of midcarpal to radiocarpal joint gradually increased and predominantly acted in the radiocarpal joint. During RUD, the lunate ($r^2 = 0.90$) moved with almost the same pattern as the scaphoid. During dart-throwing motion, the lunate ($r^2 = 0.55$) moved with almost the same contribution ratio in the radiocarpal and midcarpal joints from 10° of ulnar flexion to 40° of radial extension, but nearly plateaued or decreased on other degrees.

Discussion

This study represents a new attempt to analyze 3D motions of the wrist in vivo in a non-invasive manner. MRI was used for image acquisition to avoid radiation exposure, which has been unavoidable in previous CT-based motion analyses. Our technique can be more beneficial than CT-based analysis in clinical situations for obtaining information such as preoperative pathological kinematics of the patient and outcomes of surgical procedures in reconstructive surgery.

The volume-based registration method is based on matching of bony contour and content data in all images by similarity of the image intensity. The accuracy of this method is likely to be less sensitive to segmentation errors than surface-based registration. West et al. performed a comparative study of surface- and volume-based registrations between intermodality images of the human brain [19]. They concluded that volume-based registration tends to be more accurate than surface-based registration. Moojen et al. reported that their volume method is more accurate than a surface method in CT-based registration [11]. In a wrist kinematic study, Neu et al. reported the accuracy of 3D surface registration [14]. Rotation errors for the capitate and scaphoid were less than 0.5°, for the other bones were generally less than 2°, and for trapezoid was greater than 2°. Translation errors for the bones were generally less than 1 mm, except for the trapezoid. Our accuracy rates were similar, especially for the trapezoid, with rates for both around 2°. The poor accuracy for the trapezoid may be because of the shape of the bone. Our results correlate well with those studies, and subvoxel accuracy can be achieved, making this method very well suited to clinical applications and research.

Our data regarding global contributions during FEM and RUD largely concurred with data presented in the literature. However, the incremental contributions to wrist motion have been reported in only a few studies, and most investigations utilized in vitro studies. Recently, Crisco and colleagues reported incremental wrist motion from in vivo CT-based kinematic studies [4,20]. They concluded that scaphoid and lunate contributions to global wrist flexion changed in a linear manner with each wrist position. In our results, during DTM in vivo 3D incremental contributions changed in a linear manner, but during FEM and RUD, were not constant and changed at each wrist position, particularly for scaphoid motion.

Wrist motion in the oblique plane from radial-extension to ulnoflexion is used in many activities in daily life, such as hammering nails or throwing objects [5], and this oblique plane is believed to involve more mobility and agility [6,15]. However, kinematics of this motion data have rarely been reported, and all previous research has utilized two-dimensional or in vitro studies. Saffar and Semaan stated that a significant part of the movement takes place in the midcarpal joint during DTM, and movement in the midcarpal joint is oblique [15]. Ishikawa et al. reported that more motion of the scaphoid and lunate in the midcarpal joint was observed during DTM than during FEM [7]. Werner et al. suggested that there may be a dart throw motion during which there may be minimal scaphoid and lunate motion [17].

While our results support these conclusions in terms of the lunate (contribution of the lunate at the midcarpal joint during DTM was 80.2% in radial-extension and 77.3% in ulnoflexion), the scaphoid was found to contribute almost equally in both radiocarpal and midcarpal joints during DTM. First, these differences may be caused by differences in the plane of DTM between in vitro and in vivo. Ishikawa et al. defined the plane of DTM as at an angle of 23° to the sagittal plane. In contrast, the dart-throwing plane calculated in our study was more complex, being more functional and physiological, deviating 22.9° ± 8.8° ulnarly and pronating 17.2° ± 10.8° relative to the sagittal plane. Second, we think that dart throw motion consists of moving a combination of carpal and distal raidounlar joint. There was a tendency of the forearm being in a slightly pronated position during dart throw motion. Therefore, the movement of the scaphoid in the radiocarpal joint increased (49.6% of wrist motion). Saffar and Semaan suggested that the scaphoid displays more significant excursion in extension, sliding dorsal to the radial styloid in the dart-throwing plane. Moritomo et al. reported that the scaphotrapezio-trapezoid joint displays strong ligamentous and skeletal constraints, and therefore the direction of motion is limited to an almost 45° oblique plane relative to the sagittal plane [12,13]. We speculate that scaphoid motion in the midcarpal joint is constrained more than lunate motion, and the radioscaphoid and scapholunate joints must therefore move effectively to achieve congruent motion of the carpal bones during DTM.

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Does Three-dimensional Computer Simulation Improve Results of Scaphoid Nonunion Surgery?

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The purpose of this study was to clarify the effectiveness of the three-dimensional computer simulations in scaphoid nonunion surgery. Seven consecutive clinical patients with scaphoid nonunion at the middle third comprised the study group. Surface models of the scaphoid were constructed on the computer using computed tomography data of the bilateral wrists in neutral position. The distal and proximal fragments of the nonunion model were matched to the mirror image of the contralateral scaphoid model. The rotation of the distal fragment relative to the proximal fragment was calculated, and reduction of the displaced fragment of the scaphoid nonunion was simulated. Similarly, the estimated bone defect and the appropriate site and direction of the screw insertion were simulated. Full-sized hard models of the bone, including a model with simulated reduction and screw insertion, then were made using stereolithography based on the computer data. In the actual surgery, reduction, bone grafting, and screw insertion were achieved using the hard models as guides. All the patients obtained solid bone fusion and substantial clinical improvement with normalized scapholunate and radiolunate angles after surgery. Three-dimensional computer simulations were found as useful for accurate correction of scaphoid nonunions and proper screw placement, which consequently leads to good clinical results.

In scaphoid nonunions, the distal fragments usually rotate volarly, whereas the proximal fragments rotate dorsally, resulting in a humpback deformity with an evident dorsal intercalated segment instability (DISI) pattern of the carpal bones.[32] If the deformity is left untreated, osteoarthritis progresses initially at the radioscaphoid articulation, eventually affecting the midcarpal joint.[9,20,26,36] Incongruence of the joint surfaces and loss of carpal stability resulting from the displaced scaphoid nonunion are considered the major factors of these progressive degenerative changes.[26] Anterior wedge-shaped bone grafting has been advocated since the 1970s to correct carpal malalignment, restore normal scaphoid anatomy, and potentially avoid degenerative complications.[9,11–13,15,28,34,35] However, there has been no standard method to simulate the precise correction of this three dimensionally complex deformity.

Another problem of scaphoid nonunion surgery is the difficulty of screw insertion. Proper orientation and insertion of a screw across the ununited scaphoid may be technically difficult. The jig is not always positioned accurately to the bone. Improper placement of the screw results in loss of fixation and could be a critical cause of nonunion after anterior wedge-shaped bone grafting and screw insertion.[9]

However, during the last decade the continued developments in computed tomography (CT) hardware and computer technology have enabled simulated orthopaedic surgery with three-dimensional (3-D) models.[16,33] Since 2001, we have attempted to simulate the surgery for scaphoid nonunion using 3-D models from CT data to achieve three dimensionally accurate reductions and correct screw insertion. We wished to determine whether the 3-D computer simulation of the scaphoid nonunion helps us to reduce the displaced fragments correctly, insert the screw in the appropriate position, and as a result improve the radiographic and clinical results after the surgery?

MATERIALS AND METHODS

Seven consecutive patients with scaphoid nonunion (Table 1) comprised the study group. Inclusion criteria were nonunion at the middle third, surgery done more than 3 months after the

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Each author certifies that his or her institution has approved the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research, and that informed consent was obtained.
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TABLE 1. Patient Data

Patient Number	Age at Surgery (years)	Gender	Affected Side	Duration of Nonunion (months)	Followup (months)
1	22.1	F	R	9	15.6
2	20.2	M	L	3	15.4
3	18.2	M	R	6	12.1
4	21.9	M	L	13	13.1
5	42.4	M	L	62	15.7
6	18.4	M	L	3	12.5
7	24.2	M	L	18	15.1

initial injury, and age older than 18 years. Exclusion criteria were proximal or distal pole nonunion, fresh fracture, age younger than 17 years, and preoperative osteoarthritic change seen on plain radiographs. Six patients were men and one patient was a woman. The right wrist was affected in two patients, and the left wrist was affected in five patients. The time between injury and surgery averaged 12.6 months (range, 3–36 months). Four patients had received no treatment for the original fracture, two patients had been misdiagnosed, and one patient had chosen to discontinue the initial treatment. All patients had moderate wrist pain when using the affected hand. Patients were an average of 23.9 years (range, 18–42 years) at the time of surgery. They then were followed up for more than 12 months.

Computed tomography scans of the bilateral wrists with a slice thickness of 0.625 mm and pixel size of 0.625×0.625 mm were taken (General Electrics, High Speed Advance or Light-Speed Ultra 16, Waukesha, WI) with the patient in the prone position with the arms elevated over the head. Data were saved as Digital Imaging and Communications in Medicine (DICOM) format. To maintain the wrists in neutral position, splints made of radiolucent material were worn during image acquisition. The contour of the scaphoid bone was semiautomatically segmented using commercially available software (Virtual Place M®, Medical Imaging Laboratory, Tokyo, Japan), and a surface model of the bone was constructed by applying a 3-D surface generation of the bone's cortex using the marching cubes algorithm.[24] The geometric models of the scaphoid bone were observed using this computer program (Fig 1).

Using the graphic work station, the distal and proximal fragments of the nonunion model were matched to the mirror image of the contralateral scaphoid model using iterative closest point (ICP) algorithm, which is one of the most advanced methods for surface-based registration.[3] In this method, a 3-D surface model and a set of 3-D points are registered starting from initial transformation parameters and finally finding the best parameters, while minimizing the sum of the distance from each 3-D point to the surface. The proximal and distal fragments of the nonunion model were registered with the proximal and distal parts of the mirror image of the contralateral normal scaphoid, respectively. Therefore, the rotation of the distal fragments relative to the proximal fragment were calculated using a screw displacement axis system.[22] In this way, we simulated reduction of the displaced fragments of the scaphoid nonunion (Fig 2A).

The estimated bone defect was calculated by subtracting the reduced nonunion model from the mirror image of the contralateral normal scaphoid by means of Boolean operation using the commercially available computer software (Magics RP®, Materialise, Leuven, Belgium). The appropriate site and direction of the screw insertion were similarly simulated by observing the model transparently or observing the transverse section of the reduced nonunion models after trial insertion of the screw on the computer monitor (Fig 2B). The screw was simulated to be placed along the longitudinal axis of the scaphoid and into the center of the proximal fragment. The estimated longest length of the screw was defined as the distance between the volar and dorsal cortex of the scaphoid where the simulated screw insertion pierces.

To facilitate the reproduction of computer simulations in the actual operation, full-sized stereolithography models (hard mod-

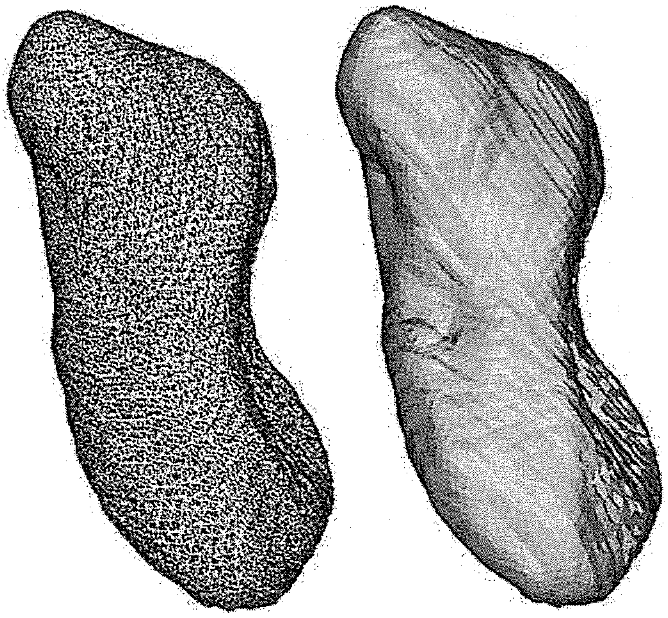

Fig 1. A 3-D surface model of the scaphoid as reconstructed by computer shows the frame model (right) and surface model (left).

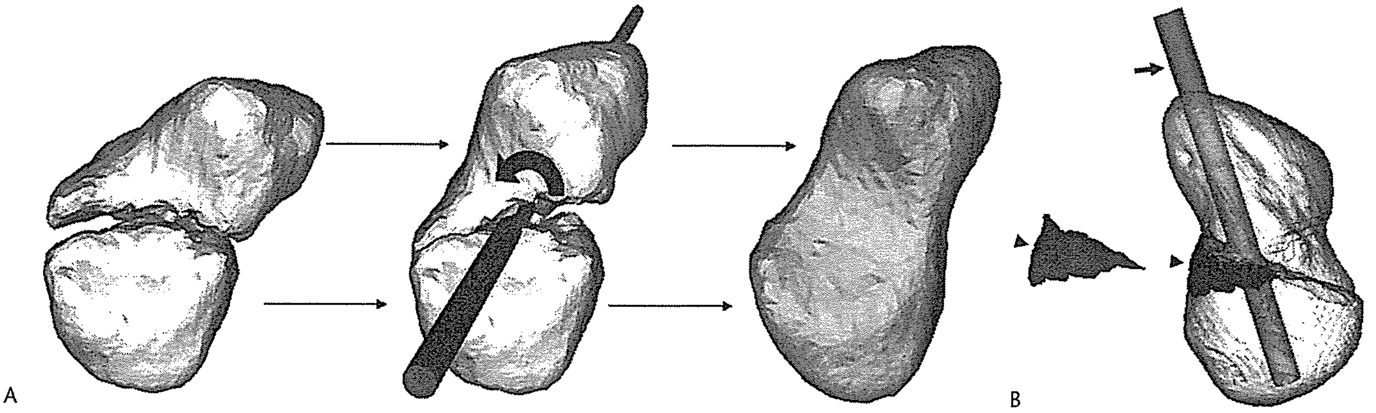

Fig 2A–B. (A) To simulate reduction of the displaced scaphoid, the distal and proximal fragments of the nonunion model (left) were registered to the mirror image of the contralateral normal scaphoid model (right). The deformity to be reduced was described as rotation around the rotation axis (middle). (B) The bone defect (arrowhead) was estimated, and the appropriate site and direction of the screw insertion (arrow) were determined by viewing the reduced scaphoid model on transparent mode from various angles.

els) of the bones (displaced nonunion in situ, mirror image of the normal scaphoid, and reduced nonunion model with simulated screw insertion) were made based on the computer data in all patients and used as guides during surgery (Fig 3). The hard models of the estimated bone defect also were made after the same method in three patients and were used as guides when shaping the bone graft. The hard models were made of epoxy resin with an accuracy of 0.01 mm (C-met Co. Ltd., Yokohama, Japan).

Surgery was done through an anterior approach. The capsule of the wrist was incised longitudinally to expose the palmar surface of the scaphoid, and the nonunion site was compared with the hard models (Fig 4A–B). The displaced distal and proximal fragments were reduced by extending the wrist to match the contour of the anterior surface of the nonunited scaphoid to the shape of the hard model in reduced position. The sclerotic bone of the nonunion site was resected to visible bleeding. A bicortical bone graft was obtained from the iliac crest and shaped to match the bone defect. With three patients, the hard model of the estimated bone defect was used as a reference during this procedure, taking into consideration the fact that the actual bone graft is

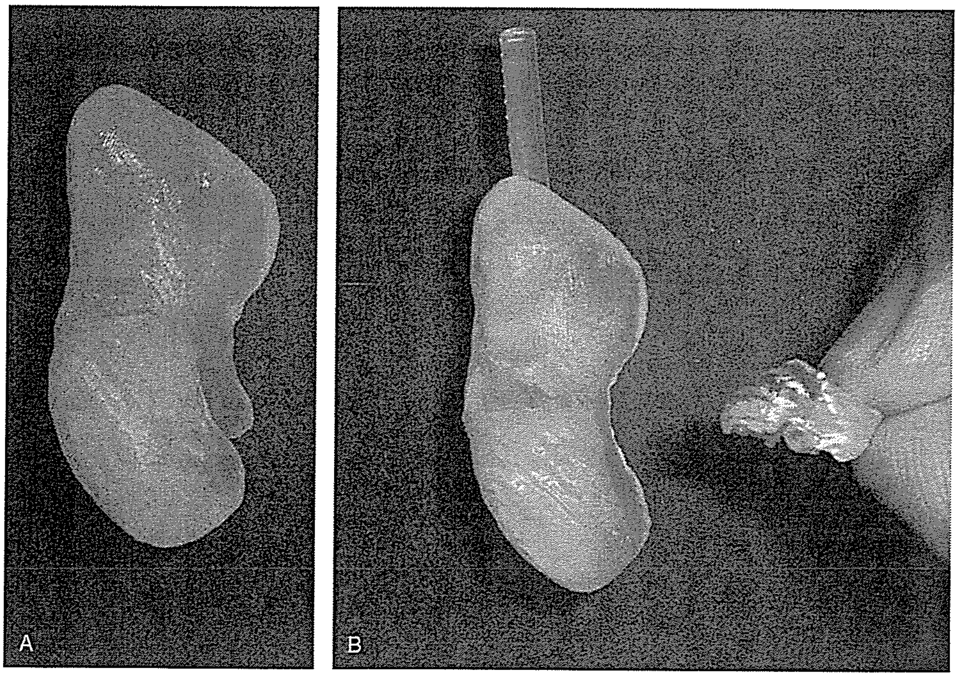

Fig 3A–B. Stereolithography of the scaphoid was made from computer data as shown in a (A) scaphoid nonunion model and a (B) reduced model with appropriate screw insertion and estimated bone defect.

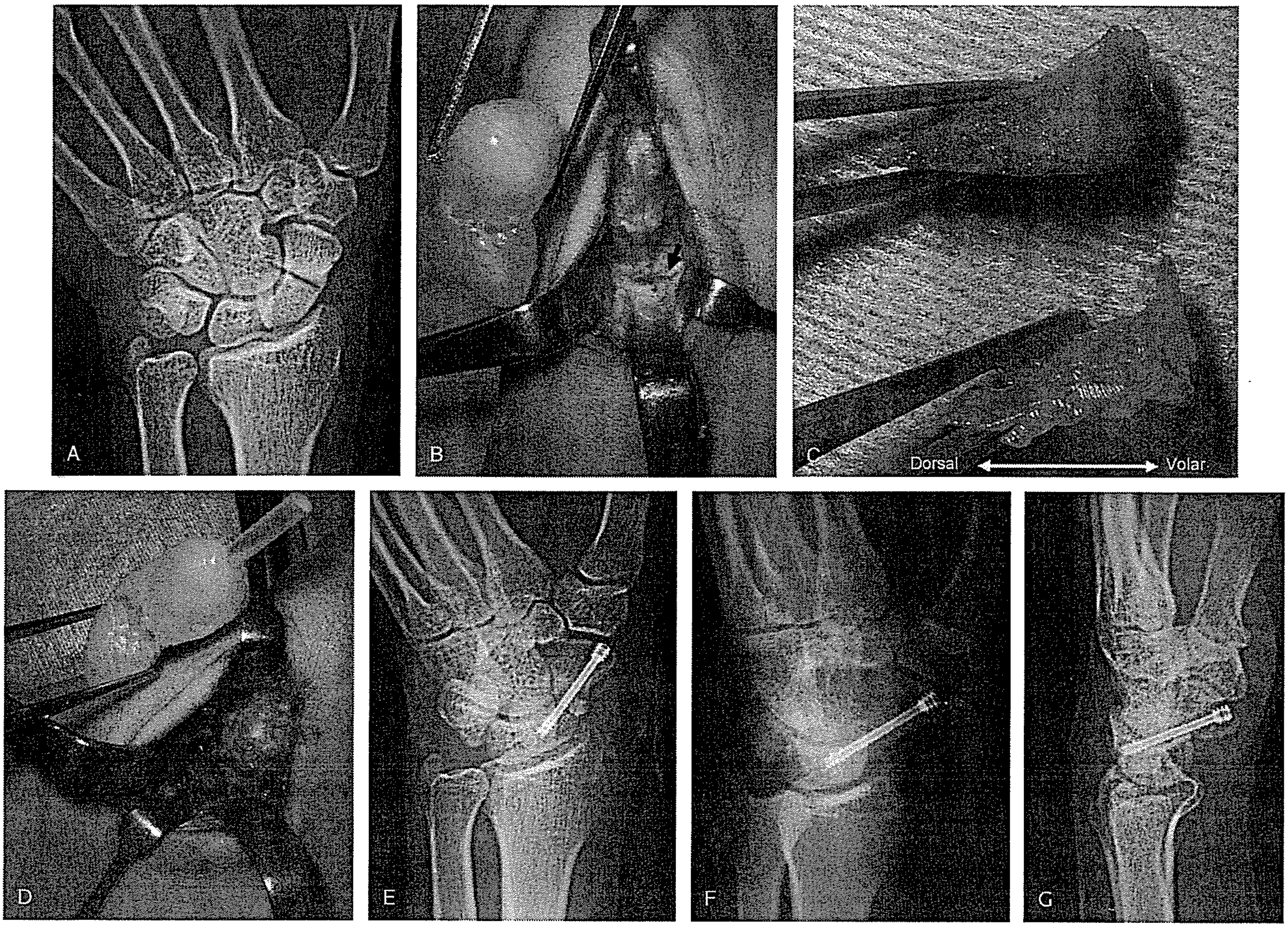

Fig 4A–G. (A) A plain radiograph shows scaphoid nonunion at the waist in Patient 7. (B) A nonunion site (arrow) was compared with the hard model. (C) The iliac bone graft was shaped using the hard model as a reference. (D) After inserting the bone graft, the site and direction of screw insertion were determined using the hard model as a guide. (E) The radiograph immediately after surgery shows good reduction of the displaced fragments and proper screw placement. (F) Anteroposterior and (G) lateral radiographs obtained 6 months after surgery show solid bone fusion with normal alignment.

larger than the estimated bone defect by the resected bone amount (Fig 4C). The graft was put into the bone defect followed by the insertion of a trial Kirschner wire (K wire) 0.8–1.2 mm in diameter to the simulated appropriate site and direction using the hard model as a guide (Fig 4D). After confirming position of the first K wire with an image intensifier, the second K wire was inserted alongside the first to prevent the scaphoid from loosening the reduction during the screw insertion. Subsequently, the first K wire was removed, and internal fixation was accomplished by placing a double-threaded screw in line with the removed K wire (Fig 4E). In patients in whom a cannulated screw was used, the screw was inserted through the first K wire. A Herbert screw (Zimmer Inc., Warsaw, IN) was used in four patients, a Scaphoid screw (Hit Medica Srl, Rimini, Italy) was used in two patients, and a DTJ screw (MEIRA Corp, Nagoya, Japan) was used in one patient. The latter two screws were cannulated variants of the double-threaded screw for small bones. The wrist was immobilized for 4 weeks postoperatively, and a short arm splint was applied until bone union was confirmed radiographically (Fig 4F–G).

To evaluate carpal alignment, the radiolunate angle (RLA), scapholunate angle (SLA), and capitolunate angle (CLA) of the plain radiographs for both wrists were measured before and after the surgery and at the most recent followup.[25] The standard deviation of the intraobserver and interobserver variations of these radiographic measurements has been reported as less than 3°.[23] Screw placement was considered appropriate when postsurgical radiographs showed its insertion along the longitudinal axis of the scaphoid into the center of the proximal fragment on the AP, lateral, and scaphoid views. Bone union was considered complete when the fracture line disappeared and the bone trabeculae continuity was confirmed on all three radiographic views.[10,31]

Clinical evaluation was done an average of 14.2 months (range, 12–16 months) after surgery, and 12 (range, 9–14 months) months after bone healing. To evaluate the clinical results, the rating system of Cooney et al[7] was used. Ratings were given to each patient as follows: pain, function status, range of motion (ROM) of the wrist, and grip strength measured by percentages of normal (range, 0–25 points). Points were accumulated for the four categories. A satisfactory result totaled 65 or more points. The clinical rating system is not a patient-generated system validated against independent measures, but has been widely used in its original or modified forms in major studies dealing with wrist problems.[2,8,17,18,34,35] Clinical ratings were made by two of the authors (TM, HM) who were the operating surgeons. Radiographic measures were made by one author (AG) who was blinded to the clinical results.

RESULTS

In all patients, normalized carpal alignment, appropriate screw placement, and solid bone fusion seen on radiographs were accomplished with satisfactory clinical results. The mean of SLA, RLA, and CLA were 69.4°, –6.0°, –3.8° before surgery and 49.1°, 2.8°, 3.9° after surgery, respectively (Table 2). The mean SLA, RLA, and CLA of the contralateral normal wrist were 49.9°, 5.0° and 8.6°, respectively. The radiographic parameters had not changed at the most recent followup. The screws were positioned appropriately in all patients as planned before surgery. On average, all patients obtained solid bone fusion by 9.6 weeks (range, 8–12 weeks) after surgery. Postoperative radiographs showed no progressive osteoarthritis. The postoperative wrist score ranged from 65–100 points (average, 89 points) (Table 3). The average flexion-extension ROM was 138° (range, 115°–160°), and the average radioulnar ROM was 64° (range, 50°–75°). Grip strength was 80–100% of the uninjured wrist with an average of 90%. One patient (Patient 4) had wrist pain on extension of the affected wrist and restricted extension ROM despite solid scaphoid union at the most recent followup. In this patient, an osteophyte at the dorsal ridge was evident on the 3-D model, although it was not evident on plain radiographs. The osteophyte was thought to be the cause of the fair result of this patient. The other patients reported neither wrist pain nor functional impairment at the most recent followup.

During the operation, stereolithography models were of great help and provided good surgical orientation. Using these hard models, we were able to reduce the nonunions and insert the screws according to the preoperative plan. Hard models of the bone defect were fabricated in three of the seven patients, and the models were useful in two patients. In the third patient, because intraoperative findings necessitated extensive resection of bone at the nonunion site, the hard model was smaller than the appropriate bone graft.

In the computer simulation, the distal fragment volarly rotated 34.8° (range, 18.7°–70.9°) relative to the proximal fragment around the rotation axis, which ran in a dorsoulnar to radiovolar direction penetrating the head of the capitate in all the patients (Fig 5). The mean volumes of the distal fragment, the proximal fragment, and the estimated bone defect were 1518 mm^3, 1346 mm^3 and 219 mm^3, respectively. The mean volume of the contralateral normal scaphoid was 3045 mm^3. The estimated bone defect was triangular, with a volar base and dorsal apex. The dimensions were 5.5 mm (range, 3.8–7.3 mm) in anterior thickness, 9.7 mm (range, 7.5–12.1 mm) in depth, and 10.7 mm (range, 9.1 to 12.8 mm) in width on average. The appropriate point of screw insertion was located 3 mm ulnar and dorsal to the center of the scaphoid tubercle. The estimated largest length of the screw was an average of 28.1 mm (range, 26–32 mm), and the length of the screw used in the actual surgery was an average of 24.3 mm (range, 22–28 mm).

DISCUSSION

Management of a displaced scaphoid nonunion is challenging. Solid bone fusion with normalized carpal align-

TABLE 2. Radiographic Evaluation

Patient Number	Time Until Bone Union (weeks)	SLA Preoperative/ Postoperative (unaffected side)	RLA Preoperative/ Postoperative (unaffected side)	CLA Preoperative/ Postoperative (unaffected side)
1	6	60/50 (45)	10/14 (17)	5/15 (17)
2	7	85/45 (50)	−17/−5 (−3)	−18/0 (3)
3	12	85/50 (45)	−12/−5 (−3)	−10/0 (2)
4	12	70/55 (60)	−13/0 (5)	0/5 (7)
5	10	65/45 (50)	0/10 (13)	−2/11 (15)
6	9	50/45 (46)	0/3 (5)	2/5 (10)
7	12	65/45 (48)	−5/0 (3)	−2/2 (3)

SLA = scapholunate angle; RLA = radioscaphoid angle; CLA = capitolunate angle

TABLE 3. Clinical Evaluation

Patient Number	Flexion/Extension Range (degrees) (F/E)	Radioulnar Range (degrees) (R/U)	Grip Strength (kg) (affected/unaffected)	Pain	Wrist Score
1	150 (80/70)	70 (20/50)	24/24	None	100
2	135 (70/65)	55 (15/40)	46/49	None	90
3	145 (75/70)	60 (20/40)	48/49	None	100
4	115 (70/45)	50 (15/35)	36/45	Mild	65
5	120 (60/60)	65 (25/40)	53/60	None	90
6	160 (80/80)	75 (25/50)	37/45	None	90
7	135 (60/75)	70 (20/50)	43/50	None	90

ment is the key to achieving good functional results.[1] The importance of anatomic reduction has been emphasized by numerous investigators.[9,13,30,34] Patients with malunited scaphoid fractures have a greater incidence of osteoarthritis and impaired wrist function than patients whose fractures unite anatomically.[2,14,25,33] Altered kinematics and intraarticular incongruity predispose the wrist to having progressive osteoarthritis develop. Tsuyuguchi et al[35] reported that substantially better functional results could be obtained in patients with normalized carpal alignment than in patients with persistent DISI deformity as seen by increased SLA after surgery. In a simulation study using cadavers, the loss of wrist extension was proportional to the angular deformity of the scaphoid, and complete loss of wrist extension occurred at 30° angulation.[5] Given these research findings, it is desirable to restore as much precise anatomic reduction as possible when treating scaphoid nonunion, although the rate of malunion after surgery has been reported to be 5.4–50%.[11,21,34,35] Fernandez[12,13] advocated the insertion of a wedge- or trapezoidal-shaped iliac bone graft of which the size was planned using preoperative radiographs through a volar approach. However, in preoperative planning based on plain radiographs, two-dimensional information does not always reliably correct carpal malalignment.[34] Concerning solid bone fusion after scaphoid nonunion surgery, appropriate screw insertion is of great importance. The optimum positioning of screw placement is difficult even under fluoroscopic control, and the rate of improper screw placement has been reported as 19–29%.[1,9] The high incidence is presumably because of the complicated 3-D configuration of the scaphoid bone.

Our approach to solving these problems was to simulate the surgery using 3-D models derived from CT data. Although 3-D CT models have been used to elucidate the pathomechanism of scaphoid nonunion,[4,6,19,27,29] the attempt to simulate the surgery for scaphoid nonunion with 3-D information has not been reported. Although the limitation of the current study includes small numbers of subjects, lack of concurrent controls, and a patient-generated validated means of outcome assessment, it is the first trial investigating the usefulness of 3-D computer simulation in this field.

In our method, the deformity could be measured three dimensionally. The amount of displacement of the distal fragment relative to the proximal fragment was expressed as rotation around a rotation axis and observed three dimensionally. Furthermore, we were able to know the estimated bone defect, the optimum site, and the direction of

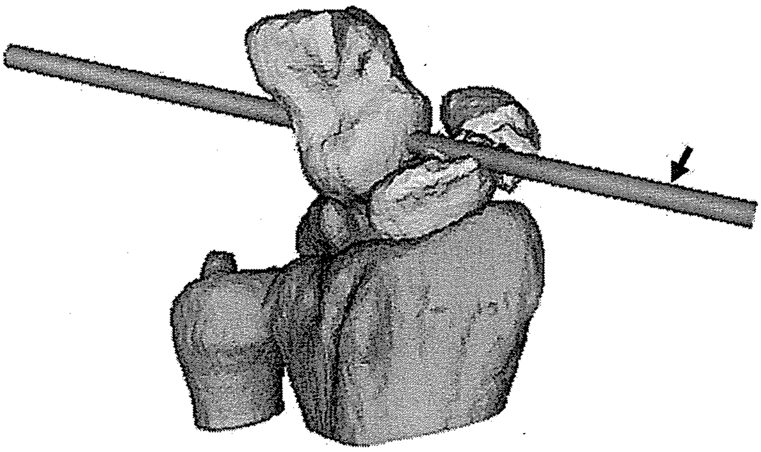

Fig 5. The rotation axis around which the distal fragment rotates runs in the dorsoulnar to radiovolar direction penetrating the head of the capitate (arrow) (Patient 3).

screw insertion. The estimated bone defect was consistently triangular, with its base facing volarly, and a width of 4–7 mm. A full-sized plastic model made by stereolithography was used to reflect the results of preoperative simulation in the actual surgery. This proved useful for acquisition of intraoperative orientation, reduction of the displaced nonunion, shaping of the bone graft, and appropriately positioned screw insertion. Radiographic results of all seven patients showed normal carpal alignment and optimal screw placement. Clinical results were either excellent or good, with the exception of one patient who had minor osteoarthritic changes seen on 3-D images but not seen on plain radiographs. These results are encouraging when compared with the previously reported incidence of malunion and improper screw placement after surgery.[1,9,11,21,34,35]

The scaphoid models we used on the computer were of only surface shells, with no internal information such as bony sclerosis, osteoporosis, or cyst formation. Although surface models are easy to handle on a computer program, they do not provide adequate information regarding the amount of sclerotic bone to be resected during computer simulation. We used hard models of the estimated bone defect as guides for shaping the bone graft in three patients. These models proved useful in two patients in whom sclerotic changes were not severe. It was not useful in one patient because of the large amount of sclerotic bone that needed resecting. The size of the actual bone graft should be determined by adding the resected amount to the estimated bone defect. This point will require improvement in the future. The other shortcoming of our method is the need for CT scanning, analysis of CT data, and hard model development. Currently, the process requires 10 minutes for CT data acquisition, 2 hours of an operator's time, and 1 hour for hard model development. It is likely that these problems will be eliminated with the advancement of computer technology.

Three-dimensional computer simulations were found to be useful in achieving accurate correction of scaphoid nonunions, and for maintaining normal carpal alignment to yield a good clinical outcome.

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IN VIVO THREE-DIMENSIONAL KINEMATICS OF THE MIDCARPAL JOINT OF THE WRIST

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Background: The human carpus is a complex joint system. Many problems that arise in the wrist are the result of an alteration of intercarpal motion. Although the midcarpal joint is a major component of the wrist joint, the global kinematics of the midcarpal joint have not been described. The purpose of this study was to provide a simplified description of the motion and function of the midcarpal joint.

Methods: We studied the in vivo three-dimensional kinematics of the midcarpal joint with use of a markerless bone-registration technique. Magnetic resonance images of the wrists of twenty-four healthy volunteers were acquired during a dart-throwing motion or flexion-extension motion of the wrist. Three-dimensional animations of the isolated midcarpal joint were created. Relative midcarpal motions were investigated qualitatively and quantitatively.

Results: The direction of the capitate motion relative to the scaphoid was always similar: it was oblique and it extended from radiodorsal to ulnopalmar in radioulnar deviation, in the dart-throwing motion, and in the flexion-extension motion. The directions of the capitate motions relative to the lunate and triquetrum inclined in a similar way, while the ranges of motion were almost unchanged. As the wrist motion changed from radioulnar deviation to flexion-extension motion, the range of the capitate rotation relative to the scaphoid decreased while the range of the lunate rotation relative to the scaphoid increased. Regardless of the type of wrist motion, the loci of the displacement of all of the joint surfaces of the midcarpal joint were located within a midcarpal ovoid space, and a line connecting the centers of the joint surfaces of the midcarpal joint could be schematized as a letter "C" entwining the midcarpal ovoid.

Conclusions: Midcarpal motion is essentially the combined motion of three types of joint systems: (1) the uniaxial joint between the scaphoid and the distal row; (2) the biaxial joint between the lunate and triquetrum and the distal row; and (3) the intercarpal joints of the proximal row, which have an adaptive mechanism that accommodates the above-mentioned two types of joint systems in the midcarpal joint.

Clinical Relevance: We advocate use of the "ovoid/C" concept to describe the function of the midcarpal joint that contributes to both the stability and the mobility of the wrist, to assist clinicians in achieving a better understanding of the kinematics of the wrist joint.

The human carpus is a complex joint system interposed between the forearm and the hand. Knowledge of intercarpal kinematics should be of value both from a basic-science perspective and from a clinical point of view because many problems that arise in the wrist are the result of an alteration of intercarpal motion[1]. There is little relative motion between the four bones of the distal row (the trapezium, trapezoid, capitate, and hamate)[2-4], whereas there is greater relative motion between the three bones of the proximal row (the scaphoid, lunate, and triquetrum)[3,5,6]. Although the midcarpal joint is a major component of the wrist joint, the global kinematics of this joint have not been described, to our knowledge.

In a previous study[7], we investigated the kinematics of the midcarpal joint during radioulnar deviation of the wrist and found that the midcarpal motion is more synchronous than had been previously reported. The axes of the rotations of the capitate relative to the scaphoid, lunate, and triquetrum during radioulnar deviation were found to be located closely in space. The isolated midcarpal motions during radioulnar deviation were found to be rotations in the dart-throwing plane of the wrist, extending from radiodorsal to ulnopalmar.

The current study is a continuation of the previous investigation of radioulnar deviation[7]; it was designed to examine midcarpal kinematics during the dart-throwing motion and flexion-extension motion of the wrist and to compare them with midcarpal kinematics during radioulnar deviation.

The purpose of this study was to provide a simplified description of the motion and function of the midcarpal joint.

Materials and Methods

The in vivo three-dimensional kinematics of the midcarpal joint in the right wrists of twenty-four healthy volunteers was studied with a markerless bone-registration technique. We separately investigated the kinematics during the dart-throwing motion in twelve volunteers and the kinematics during the flexion-extension motion in the other twelve. The average age was twenty-six years (range, twenty to thirty-two years) for the volunteers included in the analysis of the dart-throwing motion and twenty-five years (range, twenty to thirty-two years) for those included in the analysis of the flexion-extension motion. Nine men and three women participated in the study of the dart-throwing motion, and eight men and four women participated in the study of the flexion-extension motion. All volunteers consented to be included in the study.

Magnetic resonance images were acquired with the same method as was used in our previous studies[7,8]. To immobilize the elbow and the wrist at a specific angle during the dart-throwing and flexion-extension motions, a special posture device with a grip bar and goniometers was used[9]. This device has three motion axes, which all cross perpendicularly at the wrist joint and enable the wrist to move along any specific plane.

For five of the twelve wrists in the group performing the dart-throwing motion, magnetic resonance images were acquired in six positions from 60° of radial deviation/extension to 40° of ulnar deviation/flexion in 20° increments in the dart-throwing plane. For five of the twelve wrists in the group performing the flexion-extension motion, magnetic resonance images were acquired in seven positions from 60° of extension to 60° of flexion in 20° increments in the sagittal plane. For the other seven patients in each group, magnetic resonance images were acquired in three positions (a neutral position and two extreme positions). We set the dart-throwing motion as an oblique wrist motion relative to the sagittal plane of the wrist in an attempt to reproduce the motion of the throwing of a dart or the hammering of a nail.

The contours of each bone were mapped from magnetic resonance volume images, and three-dimensional surface models of the bones were constructed with use of a software program (Virtual Place-M; Aze, Tokyo, Japan)[7]. The kinematic variables were calculated by registering the bone in one position and comparing it with another. The volume registration technique employed in this study was performed with use of the same software program.

The radius and all of the carpal bones except the pisiform were registered, and the relative motion of each bone was calculated. Three-dimensional animations of the relative motions were created by gradually rotating bones around their own axis of rotation between two adjacent positions and connecting them with use of originally developed software (Orthopedics Viewer; Osaka University, Osaka, Japan). We created animations of all twenty-four wrists and compared the animations of the ten wrists subjected to incremental motion analysis with the animations of the fourteen wrists that were studied in only three positions. We observed a marked similarity between them; thus, we calculated the kinematic variables from the combined data of all wrists.

The coordinate system was constructed with use of osseous landmarks with the wrist in neutral position. The z axis (the supination-pronation axis) was defined as the long axis of the distal part of the radius. The x axis (the flexion-extension axis) was defined as a line passing through the center of the capitate body at a right angle to the z axis and parallel to a line connecting the radial and ulnar styloids. The y axis (radioulnar deviation axis) was defined as a line perpendicular to the other two axes. In our definition of the anatomical planes, we considered the sagittal plane to equal the flexion-extension plane, the coronal plane to equal the radioulnar deviation plane, and the axial plane to equal the supination-pronation plane.

Direction of Global Wrist Motion

The direction of global wrist motion was defined as a line connecting two centroids of the capitate at the two extreme wrist positions on the basis of the assumption that there is little motion between the third metacarpal and the capitate[10]. The angle between the direction of global wrist motion and the x axis of the coordinate system was calculated as viewed in the axial plane.

Midcarpal Motion

Midcarpal motion was investigated by assessing capitate motion relative to the scaphoid, lunate, and triquetrum as well as by analyzing scaphoid, lunate, and triquetrum motions relative to the capitate. If the capitate is used as a reference to determine the kinematics of the proximal row, one can observe all of the relative motions in the midcarpal joint at the same time because there is very little motion between the four bones of the distal row[2-4]. The axes of rotations[11] between the two extreme positions of the capitate relative to the scaphoid, lunate, and triquetrum were the only ones calculated. The range of motion of the capitate was calculated as an angle of rotation around each axis of rotation.

Motion Between the Scaphoid and Lunate and Between the Lunate and Triquetrum

The ranges of motion of the scaphoid and triquetrum relative to the lunate were also calculated as an angle of rotation around each axis of rotation relative to the lunate. The angle was defined as positive when the scaphoid or triquetrum rotated palmarly relative to the lunate in the wrist motion from radial deviation/extension to ulnar deviation/flexion or from extension to flexion.

Relationship Between the Midcarpal Kinematics and the Radiocarpal Kinematics

To compare the midcarpal kinematics with the radiocarpal kinematics, the axes of rotations of the scaphoid and lunate relative to the radius were also investigated. Relationships between the axes of rotations of the midcarpal and radiocarpal joints were analyzed by comparing the location of the axes of rota-